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A Review and Meta Analysis of Vibrotactile and Visual Information Displays

by Linda R. Elliott, Michael D. Coovert, Matthew Prewett,
Ashley G. Walvord, Kristin Saboe, and Ryan Johnson

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Linda R. Elliott
Human Research and Engineering Directorate, ARL

and

Michael D. Coovert, Matthew Prewett, Ashley G. Walvord, Kristin Saboe, and Ryan Johnson
University of South Florida

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14. ABSTRACT

Many studies have investigated the impact of vibrotactile cues on task performance, but the wide range of cue and task types have made findings difficult to interpret without a quantitative synthesis. We provide a systematic review of studies on vibrotactile cue effectiveness with regard to task performance, organized by types of comparisons and cue complexity. Forty-five studies met the criteria for meta-analytic comparisons. Three types of comparisons were made: (1) the addition of a new tactile cue to a “baseline” condition, (2) the comparison of tactile cues to visual cues representing the same information, and (3) the comparison of visual cues compared to a multimodal combination of tactile and visual cues representing the same information. The level of cue information complexity was also examined as a moderator. When added to a baseline task or existing visual cues, tactile cues enhanced task performance. When tactile cues replaced visual cues, however, effects are attenuated and moderated by cue information complexity. Tactile alerts are effective when replacing visual alerts, but tactile direction cues do not improve performance when replacing visual direction cues. This meta-analysis of tactile applications underscores the benefits of vibrotactile and multimodal displays, highlights conditions in which tactile cues are particularly effective, and identifies areas in need of further investigation.

15. SUBJECT TERMS

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1. Introduction

1.1 Purpose

Developments in current and future information, decision making, and control systems will enable information creation and distribution to achieve extraordinary feats and challenge operators to attain new levels of performance. While research and technology address issues of information requirements, distribution, and decision support, the problem of information overload and the challenge of optimal information display remain enduring obstacles. How can future information displays be designed to optimize information perception, interpretation, and decision making? Decision making rests on more than effective distribution and fusion of information—human interpretation will always be critical.

With the advance of new technologies, the amount of information that can be distributed and displayed has grown exponentially. Under these circumstances, poor decision making, slower response times, and generally poor performance can result because the individual is too focused on processing information rather than performing tasks (Wickens, 2008, 2002). Consequently, a major challenge in the field of Human Factors is to convey critical information as efficiently as possible (to maximize recipient comprehension and decision making), while simultaneously minimizing negative factors such as overload and distraction.

One prominent method for improving task information delivery is the use of multisensory devices, or devices which convey task information through multiple or alternative sensory channels instead of the visual channel. Such devices may aid performance by simplifying information, maximizing user comprehension, and minimizing user workload. In this report, we address the use of tactile cues as a method for improving task feedback, as observed in task performance indices. Specifically, we provide a review of studies and a meta-analysis of experiments that compared the effectiveness of tactile and visual cues, organized by informational complexity.

1.2 Background

Although a wealth of experimental research has examined the impact of tactile cues across a variety of situations, there is no comprehensive review available to summarize the effect of tactile cues on task performance. Recent reviews (Jones and Sarter, 2008; van Erp, 2007) provide information with regard to several different tactile and haptic devices, but these reviews limit their focus to perception and localization as the primary criteria of variables such as stimulus duration, frequency, and intensity. In contrast, our review addresses the effectiveness of tactile cues with task performance as the primary criterion. This review also compares the effectiveness of tactile cues with that of visual cues (instead of comparing features of the tactors themselves). In addition, our work organizes the review of vibrotactile cues around the type of task

information being provided (alert, direction, spatial orientation, communication) as a potential moderator. What follows is a brief summary of the theoretical background for this review, an overview of the study framework, and a discussion highlighting its importance.

1.3 Attention and Cognition Under High Workload

There is no doubt that visual displays enable easy and powerful perception, awareness, and comprehension. At the same time, researchers have predicted performance gains from the presentation of certain types of information using other sensory modalities such as speech, audio, haptic, tactile, and three-dimensional (3-D) (e.g., virtual reality, 3-D audio).

Two theories predict gains from a multisensory display of information. First, Wickens' Multiple Resource Theory (MRT) (2002, 2008) suggests that (1) people have several semi-independent cognitive resources; (2) some resources can be used near-simultaneously without detriment to performance, while others cannot; (3) tasks requiring the use of different resources can often be effectively performed together; (4) competition for the same resource can produce interference; and (5) dissimilar cognitive resources exist to process information from different sensory modalities (e.g., visual, audio, or tactile information). MRT defines these capacities and contingencies while predicting the degree to which information from a particular sensory channel can be effectively offloaded to another channel. In demonstrating the theory, particular attention has been paid to pilot performance (Wickens, Goh, Helleberg, Horrey, and Talleur, 2003) although there is nothing unique in that environment that would lead the theory to make differential predictions.

The effectiveness of offloading depends on many factors including: (1) overall workload (e.g., offloading is more likely to ease high workload), (2) visual attention requirements (e.g., offloading is more likely effective when there are high requirements for both focal and ambient vision), (3) cue overlap on subtasks (e.g., visual scanning and tactile/audio direction cues effectively combine to support a common task such as target detection or navigation), and (4) the degree to which separate tasks demand attention. Wickens (2002) provides extensive discussion and examples of these factors in MRT.

Whereas MRT is focused on aspects of workload and conflict in information processing, the Prenav model proposed by van Erp (2007) has a strong emphasis on performance that can be automated, such as steering, navigation, and control systems. Prenav explains how tactile cues can affect attention, cognition, and performance, with particular regard for the effects of practice, automaticity, and intuitive response. Prenav consists of two loops: the information processing loop and the workload loop. The information processing loop has the usual links from sensation to perception, perception to decision, and decision to action. However, shortcuts from sensation and perception to action are hypothesized in order to better account for skill-based performance. These shortcuts are related to concepts of automaticity (Shiffrin and Schneider, 1984), skill-based learning (Rasmussen, 1983), and naturalistic decision-making (e.g., Klein, 2008; Zsambok

and Klein, 1997). These shortcuts are proposed to reduce cognitive overload, thus preserving performance quality.

Within the Prenav model the tactile sense is described as highly intuitive and associated with fast reaction times. In fact, studies have found that tactile cues can even be faster than other sensory channels, when used for alarms or direction cues. For example, faster braking responses occurred in reaction to tactile rear-end collision warnings, compared to when visual cues were used (Scott and Gray, 2008). In another context, operators fired more quickly in outdoor target practice using targets to the left, right, and center when using torso-mounted tactile direction cues than with visual cues (Gilson, Redden, and Elliott, 2007). Tactile cues added to visual cues also yielded faster reaction times in simulation-based studies of operator decision-making and performance (e.g., Calhoun, Fontejon, Draper, Ruff, and Guilfoos, 2004; Calhoun, Ruff, Draper, and Guilfoos, 2005; Forster, Cavina-Pratesi, Aglioti, and Berlucchi, 2002).

1.4 Study Framework: Vibrotactile Cues and Informational Complexity

MRT and Prenav theories provide the background for the hypotheses and analyses in the current review. However, whereas MRT focused on workload and Prenav focused on tasks that are more easily automated (e.g., steering and control), we examined the literature by comparing task performance of users receiving visual and tactile information cues, organized by informational complexity. The framework we employed and associated studies are presented in table 1. Preliminary meta-analyses on broad cue comparisons indicated performance benefits from tactile cues in general (Prewett et al., 2006). This review organized experimental studies to further distinguish the different types of comparisons made between visual and tactile cues to specify tactile cue effectiveness.

The first analysis includes experiments with a baseline condition and a condition where tactile cues were added to the baseline (e.g., baseline visual [B] vs. tactile [T]). In this comparison, the tactile cues neither replace nor repeat information provided by any visual cues inherent in the task. The second analysis examines studies that compared visual and tactile cue conditions, where the visual and tactile cues represented the same information, but only one cue or the other is used in experimental conditions (e.g., visual [V] vs. tactile [T]). Finally, the third analysis compares conditions with visual cues against conditions with redundant tactile cues are added to reinforce the visual information (e.g., visual [V] vs. visual-tactile [VT]).

Each type of comparison is further distinguished with regard to the level of information complexity within cues. A review of the literature reveals numerous vibrotactile research studies addressing four primary purposes: tactile cues for alerts, tactile cues for direction, tactile cues for orientation, and tactile cues for communication (see table 1). Across these groupings many experiments demonstrated that tactile displays were associated with good localization or performance but did not have a baseline or visual condition. The studies included in our analyses were restricted to those that met criteria necessary for the meta-analysis.

Table 1. Organization of meta-analyses.

Studies included in Baseline Versus Vibrotactile Comparisons by Information Type	
Alerts	Hammeed et al., 2006; Ho et al., 2007; Hopp et al., 2005; Moorhead et al., 2004; Scott and Gray, 2008
Direction	Bloomfield and Badler, 2007; Chen and Terrence, 2008; Davis, 2007; Dorneich et al., 2006; Elliott et al., 2006; Glumm et al., 2006; Hameed et al., 2007; Lindemann et al., 2003; Lindeman et al., 2005; Murray et al., 2003; Tan et al., 2003
Spatial orientation	Aretz et al., 2006; Chiasson et al., 2002; Diamond et al., 2002; McGrath et al., 2004; Raj et al., 2000; Small et al., 2006; Tripp et al., 2007; van Erp et al., 2002; van Erp et al., 2003; van Erp et al., 2006
Studies included in Visual Versus Visual and Vibrotactile Comparisons by Information Type	
Alerts	Calhoun et al., 2002; Calhoun et al., 2004; Calhoun et al., 2005; Forster et al., 2002; Hopp et al., 2005; Krausman et al., 2007; Moorhead et al., 2004; Sklar and Sarter, 1999
Direction	Bloomfield and Balder, 2007; Elliott et al., 2007; Latham and Tracy, 2002; Tan et al., 2003; van Erp et al., 2002
Spatial orientation	Chiasson et al., 2002; Eriksson et al., 2006; McKinley and Tripp, 2007; van Erp et al., 2007
Studies included in Visual Versus Vibrotactile Comparisons by Information Type	
Alerts	Calhoun et al., 2002; Forster et al., 2002; Hammeed et al., 2007; Krausman et al., 2005; Scott and Gray, 2008; Sklar and Sarter, 1999; van Erp et al., 2004
Communication	Brewster and King, 2005; Ho et al., 2001; Pettitt et al., 2006;
Direction	Bloomfield and Badler, 2007; Cholewiak and McGrath, 2006; Davis, 2006; Elliott et al., 2006; Elliott et al., 2007; Glumm et al., 2006; Hameed et al., 2006; Lindeman et al., 2003; Savick et al., 2008; van Erp et al., 2002; van Erp et al., 2004
Spatial orientation	McKinley and Tripp, 2007; Small et al., 2006

1.5 Tactile Cues for Alerts

With regard to use as alerts, research participants have successfully perceived and interpreted vibrotactile cues in averse, demanding, and distracting situations, such as combat vehicles (e.g., Carlander and Errikson, 2006; Krausman and White, 2008), aircrew cockpits (e.g., Diamond, Kass, Adrasik, Raj, and Rupert (2002); Rupert, 2000a; 2000b; Rupert, Graithwaite, McGrath, Estrada, and Raj, 2004; Sklar and Sarter, 1999), unmanned aerial vehicle (UAV) operation (Calhoun, Ruff, Draper, and Guilfoos, 2005; Calhoun, Fontejon, Draper, Ruff, Guilfoos, 2004; Calhoun, Draper, Ruff, and Fontejon, 2002), high-speed watercraft (Dobbins and Samways, 2002); underwater environments (Self, van Erp, Eriksson, and Elliott, 2007), driving (Ho, Reed and Spence, 2007; Scott and Gray, 2008), and during strenuous movements (Pettitt, Redden, and Carstens, 2006; Krausman and White, 2008). Tactile alerts have been demonstrated effective for managing attention during high workload and task switching (Hameed, Ferris, Jayaraman, and Sarter, 2006; Ho, Nikolic, and Sarter, 2001; Hopp, Smith, Clegg, and Heggestad, 2005).

Users have successfully perceived and responded to tactile cues in various body locations. The placement of the tactors should correspond with task demands to provide information that easily and rapidly recognized. For example, *torso-mounted tactors* are particularly effective for alerts, direction and orientation cues (e.g., Chiasson, McGrath, and Rupert, 2002; Cholewiak and

McGrath, 2006; Elliott, Duistermaat, Redden, and van Erp, 2007; van Erp, 2007). Other locations that have been successfully used include the *wrist* (e.g., Dobbins and Samways, 2002; Brewster and King, 2005; Calhoun and Draper, 2006; Ho, Nikolic, and Sarter, 2001), *fingers* (Hameed, Ferris, Jayaraman, and Sarter, 2007; Lathan and Tracey, 2002), *palm of hand* (Tang, Beebe, and Kramer, 1997), *arm* (Bloomfield and Badler, 2007), *abdomen* (Ho, Reed, and Spence, 2007; Moorhead, Holmes, and Furnell, 2004), *shoulder* (Hopp, Smith, Clegg, and Heggestad, 2005), and *back* (e.g., Hameed, Jayaraman, Ballard, and Sarter, 2006; Jones, Lockyer, and Piateski, 2006; Lindeman, Yanagida, Sibert, and Lavine, 2003).

1.6 Tactile Cues for Direction and Spatial Orientation

Tactile direction and spatial orientation cues have demonstrated faster reaction times, better awareness of the task situation, and stable spatial orientation (Gilson, Redden, and Elliott, 2007; van Erp, 2007). Direction cues can be simple, composed of two tactors (e.g., Dobbins and Samways (2002); Moorhead, Holmes, and Furnell, 2004) or tactors situated within a glove (Latham and Tracey 2002), but are more often composed of 8–12-tactor torso belts or linear arrangements of tactors in a vest-type garment. They have been demonstrated for navigation in cars (Fitch, Kiefer, Kleiner, and Hankey, 2007, van Erp and van Veen, 2004) and simulations (Davis, 2006, 2007; Ferris, Penfold, Hammed, and Sarter, 2006; Ferris, Hammed, Penfold, and Rao ,2007; Lindeman, Sibert, Mendez-Mendez, Patil, and Phifer, 2005), and for personal land navigation (Elliott, Duistermaat, Redden, and van Erp, 2007; Duistermaat, 2005; Duistermaat, Elliott, van Erp, and Redden, 2007; Van Erp, Spapé, and Van Veen, 2003). Tactile direction cues have also been demonstrated for targeting tasks in computer-based simulations (Aretz, Andre, Self, and Brenaman (2006; Chen and Terrence, 2007, 2008; Davis, 2006; Glumm, Kehring, and White, 2006; McKinley, Gallimore, Lanning, and Simmons, 2005), high-fidelity simulations (Eriksson, van Erp, Carlander, Levin, van Veen, and Veltman, 2006; Van Erp, Eriksson, Levin, Carlander, Veltman, and Vos, 2007) and vehicles (Carlander and Eriksson, 2006). They have also been used in visual search tasks. A common approach to aid visual search uses a vibrotactile array that stimulates quadrants on the back that correspond to quadrants on the visual search area. Tactors used in this manner have been found to significantly reduce visual search time (Brill, Terrence, Downs, Gilson, Hancock, and Mouloua, 2004; Lindeman, Yanagida, Sibert, and Lavine, 2003; Tan, Gray, Young, and Traylor, 2003; Young, Hong, and Gray, 2003) and increase detection rate (Hameed, Jayaraman, Ballard, and Sarter, 2007).

Spatial orientation cues, while similar to direction cues, are distinguished based on somewhat greater complexity and purpose. Here, the goal is to provide the user with feedback on his or her position and location in disorienting environments. There has been particular investment and investigation of tactile applications for aircraft and helicopter pilot performance, resulting in many demonstrations of effectiveness for aircraft landing and hover tasks. (Chiasson, McGrath, and Rupert, 2002; Jansen, Wennemers, Vos, and Groen, 2008; McGrath, Estrada, Graithwaite, Raj, and Rupert, 2004; Raj, Kass, and Perry, 2000; Raj, McGrath, Rochlis, Newman, and Rupert, 1998; Rupert, Graithwaite, McGrath, Estrada, Raj, 2004; Small, Keller, Wickens, Socash,

Ronan, and Fisher, 2006; Rupert, 2000a, 200b; Van Erp, Veltman, Van Veen, and Oving, 2003; Van Erp, 2005; Van Erp, Groen, Bos, and van Veen, 2006; Van Erp, Veltman, and Van Veen, 2003).

1.7 Tactile Cues for Communications

Tactile patterns (e.g., tactons, tactile melodies) have been shown effective for communications (Brewster and King, 2005; Brill and Gilson, 2006; van Veen and van Erp, 2003). This is an emerging area of research, so that studies are limited and often focused on localization and correct interpretation; there are few studies that compare tactile communications with visual communication cues.

1.8 Hypotheses

Regarding vibrotactile cue effectiveness and information complexity, MRT and Prenav theories yield predictions that guide this review's hypotheses. MRT emphasizes that multisensory displays are more effective when workload is high with multiple non-conflicting tasks. Based on this perspective, we expect that the addition of *unique* or *complementary* vibrotactile cues will facilitate effective task performance across a range of task demands. On the other hand, tactile cues that replace visual cues will not provide multisensory cues, but rather replace one modality cue for another. Thus, we expect tactile cues to improve performance when added to a baseline task or when complementing existing visual cues. We predict that replacement cues, however, will not significantly improve performance beyond the level achieved with visual cues.

H1: Conditions which use *complementary* vibrotactile cues will have stronger performance scores than baseline conditions or visual-only cues (baseline versus tactile [BvT], visual versus visual-tactile [VvVT]).

H2: Conditions which use vibrotactile cues to *replace* visual cues will not lead to higher levels of performance than conditions that use visual cues only (visual versus tactile [VvT]).

Prenav predicts that tactile cue effectiveness depends on the type of information provided by tactile cues, primarily because certain tactile cues are more intuitive. In particular, this approach anticipates benefits in tactile alert, direction, and spatial orientation cues, because they are more easily processed by device users. Using the Prenav model, we expect that tactile cue efficacy will depend upon the complexity of information being presented. Specifically, we hypothesize that conditions using tactile cues for alerts, direction, or spatial orientation will exhibit a stronger effect than the more complex communication cues.

H3: The advantage of tactile cues over baseline visual cues will be moderated by the informational complexity of the cue, in which alerts, direction, and spatial orientation cues will exhibit a stronger mean difference statistic than communication cues.

1.9 Need for Meta-analysis

Although existing research has generally indicated that tactile cues benefit performance, much of the available evidence is weak when assessed individually. Many studies use small samples in which the influence from a single individual could disproportionally impact the outcome. Study conclusions are often based exclusively on the *p*-value associated with an obtained point estimate. It is well known that an obtained *p*-value poorly predicts any future obtained *p*-value, even when the *p* is obtained from large samples. Cumming (2008), for example, demonstrated that if an initial experiment results in two-tailed $p = 0.05$, the *p* – interval (e.g., the range of *p*-values that is likely to occur upon experiment replication) is very large. Using *p*-values is also a problem for the small sample studies observed in this area, primarily because there is a greater chance to obtain a strong effect with a small sample size. With small samples, a single outlier has a larger influence on mean differences. This is not the case in larger samples where any individual case has a lesser influence on the overall computed statistic (e.g., the F ratio). Furthermore, a focus exclusively on statistical significance ignores the value of the effect size. For example, two statistically significant (or insignificant) effects may differ by a magnitude that yields notable differences in task performance.

Because of the strong requirement to replicate and validate small study findings with a larger sample size, there is a need for a meta-analysis of tactile displays and task performance. Such an endeavor addresses the weaknesses of individual experiments by computing an average statistic derived from many studies and samples. A meta-analytic review not only serves to validate results of individual experimental studies, it also highlights the differences between cue complexities and experimental focus that exists between studies (e.g., different independent variables). Recent reviews (Jones and Sarter, 2008; van Erp, 2007) provide comprehensive information with regard to several kinds of tactile and haptic devices and discuss the characteristics that affect perception and localization, such as stimulus type, duration, frequency, and intensity. However, they did not address the effectiveness of tactile arrays for task performance, nor did they test the impact that informational complexity has on these relationships. We argue that the perception of tactor arrays and patterns is not sufficient if the cue does not improve task performance.

The current study addresses the need for a review of the relationships between cue modality, cue complexity, and task performance. Our work fulfills this need via meta-analysis of experiment-based comparisons of vibrotactile and visual cues in relation to task performance. To further clarify the context, these studies are further organized by cue information complexity.

2. Method

2.1 Literature Search

Multimodal research is being performed in disparate disciplines. As such, key terms (e.g., multimodal, audio, tactile, haptic, interface, display) were searched using the following databases: Association for Computing Machinery (ACM), Institute of Electrical and Electronics Engineers (IEEE), IngentaConnect, PsycInfo, Web of Science, Defense Technical Information Center (DTIC), and Cambridge Scientific Abstracts (CSA). Next, a seven-year retrograde hand-search was conducted on the table of contents for the following journals and conference proceedings: Human Factors, Human Computer Interaction, Military Psychology, Eurohaptics, Society of Industrial and Organizational Psychology, and Institute of Electrical and Electronics Engineers. Moreover, the references cited in relevant articles were back-checked to identify additional studies. Finally, a number of articles were deemed eligible for inclusion, but lacked the statistics (e.g., standard deviations) necessary for meta-analysis. In such cases, the primary and/or secondary authors were contacted in an attempt to obtain the requisite statistics for inclusion. Study information was entered into a Web-based bibliographic reference database (Coovert, Walvoord, Elliott, and Redden, 2008) and is available upon request.

Inclusion Criteria

To be included in the meta-analysis, studies had to belong to one of three categories of comparisons. In the BvT analysis, *tactile cues adding additional information are evaluated against a baseline task situation*. Examples include adding tactile alerts to a command and control decision task or adding tactile direction cues to a simulated driving task. In the VvT comparison, *tactile cues are evaluated against a condition where visual cues portray the same information*. This included studies comparing visual versus tactile cues for alerting or navigation functions. In this comparison, the tactile cue condition replaces a visual cue with a tactile cue. In the VvVT comparison, *visual cues are evaluated against the combination of visual and tactile cues representing the same information*. This is a comparison of single versus multisensory display conditions. Only studies with experimentally controlled manipulations (e.g., in which cue conditions are assigned) were included. This eliminates the more naturalistic studies in which subjects were able to choose which cues to use. We also screened studies for the quality of visual and tactile cues. Comparisons were limited to studies that compared cues that were accurate and reliable. Thus we excluded some interesting studies that manipulated cue reliability since our focus is not on the trust associated with a cue. We also did not include studies of cross-modal interactions using cues that were counterintuitive (e.g., where a tactor or visual cue on the left was used to cue an event to occur on the right). Although those studies have reason and purpose, they are not appropriate for these analyses as our interest is on the effectiveness of the cue itself, not on boundary conditions associated with the cue's use.

In addition, eligible studies had to compare modalities in relation to task performance indices (e.g., user errors, completion time, and/or reaction time). We did not include perception as an outcome nor subjective ratings of workload, preference, or evaluations of device characteristics. Studies that used computer mice or joysticks with haptic or tactile features were also not included in these comparisons, as they are the focus of a separate meta-analysis. Studies with pathological participant populations (e.g., deaf, blind) or with sample sizes of less than four were not included. Lastly, studies with the required modalities and outcome variables were excluded if we were unable to obtain enough information to calculate an effect size (i.e., information was not reported in an article and the authors failed to respond to requests for statistics).

2.2 Procedure

Study Coding

Studies meeting the selection criteria were evaluated on the following dimensions: (1) article characteristics (source used to identify the article, type of publication), (2) sample characteristics (age, gender, participant population), (3) research design (setting, within vs. between comparisons, random assignment, counter-balancing), (4) modality comparisons (BvT, VvT, and VvVT), (5) outcome variable (e.g., error rate, completion time, reaction time), and (6) cue information complexity (alert, direction, spatial awareness, communication). Ratings were recorded for reliability analyses, and initial differences in ratings were resolved through consensus meetings.

A few studies reported multiple outcome measures; for example, a study may have included more than one measure of task error. Using multiple effect sizes (due to multiple criteria) in the same analysis would violate the assumption of independence. For those cases, the most representative single measure was selected for inclusion. If the criterion measures did not differ in quality and also represented similar outcomes (e.g., two types of error), the two effect sizes were averaged. When studies reported *different* types of outcomes (e.g., errors and navigation time), they were averaged if they were both expected to be influenced by the focal cue of the study (visual or tactile). For example, if the visual or tactile cue is providing direction information for navigation during target acquisition, the direction information from the tactile cue was expected to enable navigation and also allow more visual attention to look for targets. Thus, relevant outcome measures could include waypoint completion, navigation time, and target detection rate. In this way, multiple measures comprised the combined effect size estimate when appropriate.

Reliability Analyses

For categorical variables (modality comparison, outcome variable, task level, task type, and workload), a kappa coefficient was computed to assess reliability. Coefficients ranged from 0.84 (outcome) to 0.90 (modality comparison), indicating acceptable reliability levels for the ratings. Initial rater consistency on effect sizes was modest, due to the many ways an effect size could be

obtained from the study (e.g., due to numerous outcomes). Thus, an intraclass correlation coefficient using two of five random raters ($ICC_{2, 5}$) (Shrout and Fleiss, 1979) was calculated after the consensus meeting. Inter-rater reliability is 0.92 for effect size ratings.

Calculation of Statistics

A random effects model (Hunter and Schmidt, 2004) was used for the analyses because variance was assumed to stem from study characteristics as well as sampling error, whereas the fixed effects model only assumes sampling error. As a result, random effects models attribute less variance to the treatment effect than fixed models, resulting in wider confidence intervals and a more conservative test. Analyses were conducted using the procedures of Hedges and Olkin (1985) as applied in Comprehensive Meta-analysis (CMA) 2.0 (Borenstein, Hedges, Higgins, and Rothstein, 2005). This procedure weights studies by the inverse of their error variance, such that studies with higher standard errors for their test statistic receive lower weights. Analyses yielded Hedge's g, which is preferred in that it corrects for a small-sample bias where the standard error (SE) is overestimated (Hedges, 1981). For within-groups studies in which paired correlation data were not available, we estimated a correlation of 0.3 to 0.5, using the more conservative estimate if there was a difference in overall effect size. Since they are not relevant here, we did not correct for measurement artifacts (e.g., for restriction of range, unreliability), which would be done if the focus of our study were an issue such as test validation for personnel selection (Hunter and Schmidt, 2004).

The Hedges and Olkin (1985) procedure also estimates the amount of variance among the included studies that exceeds what one would expect from sampling error alone (the random effects variance component [REVC]). Whereas the REVC is a technical number used in meta-analytic calculations, the percentage of total variance that cannot be accounted for by sampling error is more intuitively presented as I^2. We also report the SE associated with Hedge's g, as well as 95% confidence and credibility intervals. Whereas confidence intervals present the precision and possible range of the meta-analytic statistic, credibility intervals reflect the expected distribution of effect sizes within the population of studies. Confidence intervals are calculated from Hedge's g and the SE; credibility intervals are calculated from g and the REVC.

Moderator analyses were conducted using the analog to analysis of variance (ANOVA) procedure (Hedges and Olkin, 1985). This procedure treats studies in different coding categories as independent groups and determines if their effects are statistically different. Significant study heterogeneity (Q_{total}) in overall analyses indicates a possibility that the overall effect is impacted by a moderator variable. Chi square tests then compare within-group variance to between-subgroup variance (Q_b), yielding a test of moderation.

Finally, in any meta-analysis there is the threat of publication bias, whereby the sample of studies used in the analysis is skewed due to the publication process. Statistically insignificant studies are less likely to be pursued or published and tend to be under-represented in meta-analytic samples. To detect publication bias, we created funnel plots to graphically observe the

distribution of studies by sample and effect size. The presence of publication bias is detected by an asymmetric graph, in which small-sample studies only co-occur with large effect sizes, but large-sample studies contain both small and large effects (for a review, see Light and Pillemer, 1984; Hunter and Schmidt, 2004, pp. 501). In addition to funnel plots, a classic fail-safe N can be calculated. This statistic estimates the number of missing null studies ($g = 0$) needed to turn the significant results found in a meta-analysis into an insignificant one (Rosenthal, 1984).

In sum, the funnel plots provides a visual depiction of the relationship between sample size and reported effect size in order to reveal if a bias exists in reported studies. The fail-safe N tells how many studies with non-significant results would have to be added to a significant meta-analytic finding to turn it into a non-significant one. Combined, the information provided by the funnel plots and the fail-safe N allows us to gauge the confidence of our findings. Due to space constraints we do not provide the funnel plots as they collaborate the reported fail-safe N.

3. Results

Table 2 presents the meta-analytic statistics (described previously) for our work. In general, tactile cues lead to increased task performance across all three comparisons. We now present results for meta-analyses associated with each hypothesis.

Table 2. Meta-analytic results for vibrotactile cue effectiveness.

Comparison	k	g	SE	95% CI	95% CV	REVC	I^2	Q_{total}	Q_b	Fail-safe N
<u>Overall Analyses</u>										
BvT	26	1.15**	0.21	(0.74, 1.56)	(0.02, 2.28)	0.335	78.10	114.16**	0.31	1709
VvT	23	–0.95	0.22	(–0.41, 2.32)	(–1.02, 2.92)	1.011	92.02	288.09**	23.13**	198
VvVT	17	0.89**	0.18	(0.53, 1.24)	(–0.01, 1.79)	0.210	65.49	46.36**	1.63	431
<u>Analyses x Cue info</u>										
BvT								114.16**	0.31	
Alarms	5	1.60**	0.36	(0.90, 2.29)	(–0.60, 3.80)	1.255	90.33	41.38**	—	89
Direction	11	0.91**	0.21	(0.50, 1.32)	(0.25, 1.57)	0.114	58.22	23.93**	—	279
Spatial Orientation	10	1.13**	0.24	(0.66, 1.60)	(–0.24, 2.50)	0.490	81.46	48.53**	—	215
VvT								288.09**	23.13**	
Alarms	7	1.81**	0.45	(0.92, 2.69)	(–2.15, 3.05)	1.760	90.58	63.71**	—	99
Direction	11	–0.20	0.29	(–0.78, 0.37)	(–1.80, 1.40)	0.665	90.04	110.46**	—	—
Communication	3	2.29**	0.61	(1.09, 3.49)	(–0.74, 5.32)	2.390	95.00	39.98**	—	63
Spatial Orientation	2	-0.02	0.70	(–1.40, 1.36)	(–0.02, -0.02)	0.000	0.00	0.31	—	—
VvVT								46.36**	1.63	
Alarms	8	1.08**	0.24	(0.62, 1.55)	(0.02, 2.14)	0.294	68.47	22.20**	—	124
Direction	5	0.64*	0.26	(0.12, 1.15)	(0.19, 1.10)	0.054	41.41	6.83	—	24
Spatial Orientation	4	0.93**	0.40	(0.27, 1.60)	(–0.68, 2.54)	0.674	78.28	13.82**	—	15

Note. B=Baseline, V=Visual, T=Tactile. k = number of studies; g = weighted mean difference; SE = Standard error of g; * p<0.05, ** p<0.01; CI = Confidence Interval; CV = Credibility Interval; REVC = random effects variance component; I^2 = percentage of between-study variance that is not sampling error; Q_{total} and Q_b reflect total variance and the between-category variance, respectively; Fail-safe N is the number of studies where g =0 that is needed to make g insignificant.

3.1 Baseline versus Tactile

The comparison between tactile cues and a baseline condition was the most common one found in the literature. Studies of this type are relatively homogenous in characteristics. Typical examples are provided by Elliott and colleagues (2006) and Dorneich et al. (2006), whose work examined actual land navigation (and secondary tasks) in the field. Most other studies were based on simulation and virtual reality (VR) based situations. Performance measures varied, but most reflected some type of speeded performance (e.g., reaction time, time to navigate, number of targets or icons found in speeded situations, and so forth).

Hypothesis 1 stated that adding tactile cues to a baseline would improve task performance. This hypothesis was generally supported as nearly all studies favored the tactile condition. Overall, Hedge's g was 1.15 (SE = 0.21, $p < 0.01$). Although nearly all studies reported a positive effect in tactile cues, there was significant variation in study effect sizes ($Q_{total} = 114.16$, $p < 0.01$), indicating the potential for moderators.

Moderator analyses by cue complexity, however, were not significant ($Q_b = 0.31$, n.s.). Each type of tactile cue provided a significant benefit to tactile performance compared to baseline conditions: alerts (g = 1.60; SE = 0.36, $p < 0.01$), direction cues (g = 0.91, SE = 0.21, $p < 0.01$), and spatial orientation cues (g = 1.13, SE = 0.24, $p < 0.01$).

We can have a good deal of confidence in these findings. Although the funnel plot dispersion indicated more small-sample studies with positive effect for tactile cues, the fail-safe N reveals that it would take 1709 "missing" studies with null findings to change the obtained results.

3.2 Visual versus Tactile

Visual and tactile alerts or direction cues were compared for a variety of tasks, including simple reaction time or visual search (cf., Forster et al., 2002), simulated driving and/or targeting tasks (e.g., Davis, 2006), complex cockpit, UAV, or command simulations (e.g., Sklar and Sarter, 1999), as well as communicating information (e.g., Redden, Carstens, Turner, and Elliott, 2007), localizing from dense multi-tactor displays (Cholewiak and McGrath, 2006), land navigation in the field (e.g., Elliott et al., 2007), and orienting in virtual environments (Bloomfield and Badler, 2007).

Hypothesis 2 stated that tactile cues would not be effective when replacing visual cues and was partially supported. Hedge's g was not significant for this comparison, primarily due to the conservative test of the random effects model. Although the effect of replacing visual cues with tactile cues was large ($g = 0.95$, SE = 0.22), significant variation ($Q_{total} = 288.89$, $p < 0.01$) prevented a statistically significant result. We note that a more liberal, fixed effects model would find this mean difference statistically significant. The effectiveness of replacing visual cues with tactile appears to be highly dependent upon other experimental factors, as judged by the strong variation between individual studies.

Moderator analyses by cue complexity revealed a significant interaction ($Q_b = 23.13$, $p < 0.01$). Examination by type reveals tactile cues for alerts ($g = 1.81$, SE = 0.45, $p < 0.01$) and communication ($g = 2.29$, SE = 0.61, $p < 0.01$) lead to stronger performance; this is not the case for cues relative to direction ($g = –0.20$, SE = 0.29, n.s.) and spatial orientation ($g = –0.02$, SE = 0.70, n.s.).

Hypotheses 3 specified alert, direction, and spatial orientation cues would aid performance more so than communication cues. Results were consistent with predictions for alerts, but not for other types of cues. Inspection of the funnel plot is satisfactory and the classic fail-safe N computes to 198, meaning it would take 198 studies with non-significant findings to change our results.

3.3 Visual versus Visual-Tactile

VvVT studies ranged from simple reaction time or tracking tasks (e.g., Moorhead et al., 2004) to more complex demands such as communications (e.g., Bloomfield and Badler, 2007), driving (e.g., van Erp et al., 2002), cockpit or command, control, and communications (C3) simulations (e.g., Calhoun et al., 2004), land navigation (Elliott, 2007), teleoperation in VR environments (Lathan and Tracey, 2002), advanced tactile arrays for spatial orientation in flight (e.g., Chiasson et al., 2002), or localization of a dense array of tactors (Tan et al., 2003). When comparing visual only cues to complementary visual and tactile cues, we predicted a difference between conditions in favor of multisensory conditions (Hypothesis 1). This prediction was strongly supported as nearly all studies demonstrated a positive effect ($g = 0.89$, SE = 0.18, $p < 0.01$). There was also significant (though small) variation in the effect magnitude ($Q_{total} = 46.36$, $p < 0.01$), suggesting that cue complexity may yet moderate this comparison.

Re-analyses based on cue complexity revealed a non-significant moderation effect ($Q_{b\,=}$ 1.63, n.s.). Direction cues produced a marginally weaker effect size ($g = 0.64$, SE = .26, $p < 0.05$) than alert ($g = 1.08$, SE = .24, $p < 0.01$) or spatial orientation cues ($g = .93$, SE = .40, $p < 0.01$). However, these differences were not strong enough to confirm a significant interaction by cue complexity.

Inspection of the funnel plot suggested some heteroscedastic dispersion. However, the classic fail-safe N is 431, signaling a large number of “missing” studies with non-significant results would be needed to reverse the conclusion that adding tactile information to visual will increase performance significantly beyond that found in a visual-only system.

3.4 Overall Summary of Results

When added to a baseline task to existing visual cues, the addition of tactile cues enhanced task performance. Using tactile to replace visual cues produced mixed results that were moderated by cue information complexity. Tactile alerts were effective when replacing visual alerts, but tactile direction cues did not improve performance when replacing visual direction cues.

4. Discussion of the Effectiveness of Tactile Cues

This review addressed a need to understand when, why, and how tactile cues enhance task performance. We first discussed two theoretical approaches (Wickens' MRT, van Erp's Prenav) to tactile cues and then provided a quantitative review of the literature to determine empirical performance benefits. To conduct our review, we developed a framework that organized studies by the type of comparison and by the complexity of information conveyed in the cue. We predicted that tactile cues would be more effective when adding unique task information (e.g., to a baseline) or when adding redundant task cues (e.g., added to a visual cue). Conversely, we expected a smaller influence when tactile cues were used to replace visual ones. Study results generally confirmed these predictions. In addition, we expected that tactile cues would be more effective in intuitive applications (e.g., cues for alerts, direction, and orientation). Study results partially confirmed this expectation, as cue complexity moderated the relationship between visual and tactile cues as replacements (VvT), but this effect was not observed in other comparisons. Specifically, tactile cues effectively replaced visual cues when providing alerts and communications, but they did not provide an advantage when giving information on direction or spatial orientation.

4.1 Adding Tactile Cues to Support Performance

When tactile cues were added to a baseline task, all subgroup analyses were significant, including alert, direction, and spatial orientation cues. There were no studies in this comparison category that used tactile cues for communication cues. Tactile cues are found to be very effective when used to manage attention and to support tasks such as visual search, navigation, driving, target acquisition, and piloting.

4.2 Use of Multisensory Cues

Tactile cues are also effective when used in a multisensory presentation. Comparisons from this review suggest using multisensory over visual cues to convey task information. Results when using tactile information as alerts favor tactile cues, with only one study having a confidence interval that included zero (indicating the results are not conclusive). Subgroup analysis for directional cues also significantly favors the multisensory condition. Finally, studies comparing VvVT cues for orientation also favored a multisensory presentation.

4.3 Replacing Visual Cues with Tactile Cues

Results for studies that compared a tactile to a visual presentation of the same information indicate considerable variation among studies. Studies using tactile cues as alerts or communication tended to support use of tactile cues. However, while tactile communications were favored, it must be noted that they were contrasted with hand and arm signals (vs. verbal

communications). Thus, additional research is needed that compares the effectiveness of tactile communication with verbal/audio communication.

In contrast, studies using tactile direction or spatial orientation cues to replace visual ones did not yield a significant effect, though few studies examined spatial cues. It is worth noting that the benefit of replacing visual direction cues with tactile direction cues varied significantly between studies.

An examination of studies in which tactile cues did not enhance performance fails to indicate a single explanation, but rather suggests a number of situational factors that might influence results. Consider the fact that a rich variety of direction cues occur in experiments, yet were combined in this meta-analysis. Glumm et al. (2006), for instance, examined effectiveness of a torso-based tactile array that provided targeting information in a PC-based single screen simulation. The visual icon was within operator view at all times and exactly matched the targeting control device in appearance. Thus, the visual cue was easily seen, always in view, and intuitively comprehended. Consequently, operators performed very well with the visual cues. In another example, Davis (2006) compared a torso tactile belt to visual icons in a PC-based single screen simulation. The visual icon was also readily seen, always in view, very easily comprehended (i.e., a moving map), and was also associated with better performance. In contrast, Savick et al. (2008) and Krausman et al. (2005) used PC-simulations, but required the operator to look at multiple screens. This forced operators to divide attention, searching for incoming information on yet additional screens. In these situations, the tactile cues were more effective as an alert and a directional cue. These contrasting results are entirely consistent with MRT theory, in that the tactile cues were more effective when workload was higher and comprised multiple tasks needing a high degree of attention management.

Another set of conflicting results is found when tactile cues support land navigation. Elliott et al. (2006) documented a positive relationship between the tactile presentation of navigation (direction) information and task performance. Conversely, a follow-up study (Elliott et al., 2007) found that visual and multisensory cues were associated with higher performance when the visual cue was more easily comprehended. The visual display used in the latter study was very simple, using an intuitive arrow display from a commercial handheld global positioning system (GPS), compared to the more effortful standard Army alphanumeric display used in the former study. Other differences between studies include those commonly found in the field environment, such as participants navigating in daylight conditions versus night operations, good versus adverse weather conditions, and so forth. Another factor that may have affected navigation time with the tactile belt is operator familiarity and trust. Although participants rapidly learned how to use the tactile belt and were told they could not “outrun” the signals, they reported that they tended to increase speed only after they had used the system for a while. Similarly, ratings of the operational effectiveness of the tactile belt increased significantly between pre-experiment and post-experiment assessments. In summary, a closer examination of

studies suggest that tactile cues support waypoint land navigation, particularly when visibility is low or attention must be focused on local terrain (e.g., obstacles, dangerous terrain).

5. Conclusions

5.1 Strength of Findings

Use of Hedge's procedure requires complete data from primary studies, such as the standard error of the statistic, the study effect sizes (mean difference), and sample size. One might assume this is a limitation to our meta-analysis because many studies that met preliminary experimental criteria did not report complete data for calculating Hedge's g and the SE. Also, indicators of variance or confidence intervals were sometimes not reported. In addition, F tests were reported for multiple groups, but there is no reference to planned or follow-up paired comparisons, and detailed results (means, variance, t or *p* values) are often not reported for non-significant comparisons. We argue, however, that using a conservative set of criteria for article selection in meta-analysis will yield a solid foundation of articles from which to conduct the meta-analysis. As a result, because the data employed for the meta-analysis has been thoroughly examined and vetted, our findings and conclusions are veridical and conservative.

The results of every significant meta-analysis should be examined via the funnel plot and classic fail-safe N to ensure the conclusions are warranted. In our case, the funnel plots are all reasonable, and the aggregated effect size for each comparison is high. Classic fail-safe N tests for each comparison indicate that the results are robust, as the statistic ranged from several hundred to nearly two thousand non-significant studies that would have to be added to the meta-analysis in order to change our conclusions.

5.2 Future Research

Although our conclusions provide a solid foundation upon which to build, there was still significant variation in study comparisons that were not accounted for by cue complexity (as indicated by the heterogeneity statistics). Further research in this area should clarify moderating factors and refine guiding principles to determine when, where, why, and how to best use tactile cues in support of operator performance in demanding or complex environments. For example, research should ascertain the effects on levels of performance complexity, from simple reaction times to complex decision making under uncertainty. Workload was ultimately excluded from our review because very few studies manipulated or measured subjective workload in a systematic manner. Future studies also need to further test and refine theory-driven predictions with regard to overall workload and demands for attention management. Additional experiments should examine individual differences, particularly with regard to attention management skills, task experience, and automaticity. Attention management and other cognitive skills can be assessed via PC-based cognitive batteries such as the Automated Neuropsychological

Assessment Metrics (ANAM) (Reeves, Winter, Kane, Elsmore, and Bleiberg, 2001) and the Synwin task (Elsmore, 1994).

To date, experiments have focused on short-term performance, in which tasks are performed by novices or are associated with short periods of training. There is reason to believe that “ease of comprehension” is a critical factor in the design of any perceptual cue, be it visual, audio, or tactile. This begs several questions. To what degree will initial differences among cue displays last? Can such differences be overcome or reversed with extended practice? Research comparing alternate and multiple modalities of cue information should be performed in task situations where these factors can be effectively manipulated and controlled; these designs would further predict and model the impact of levels of task demand and cue complexity. Finally, we must consider effects across different task demand situations, from stationary control operators to expert first responders in an emergency environment. Principles cannot be applied regardless of situation. Instead, designers must always consider in detail the specific cognitive and situational demands, in order to best determine where bottlenecks occur and how they can be alleviated.

In summary, we provide a comprehensive analysis of the impact of vibrotactile cues on task performance. In order to distinguish different effects of tactile cues, we differentiated between comparison types and cue complexity in our analyses. Results demonstrate positive evidence for the effectiveness of tactile cues, but benefits are not as distinct when tactile cues replace, rather than complement, visual cues. Results are also consistently positive for multisensory applications. The variation among studies indicates the need for careful consideration of task demands and cue characteristics by interface designers.

6. References

An asterisk indicates inclusion in the meta-analysis.

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List of Symbols, Abbreviations, and Acronyms

ACM	Association for Computing Machinery
ANAM	Automated Neuropsychological Assessment Metrics
ANOVA	analysis of variance
B	baseline visual
BvT	baseline versus tactile
C3	command, control, and communications
CMA	Comprehensive Meta-analysis
CSA	Cambridge Scientific Abstracts
DTIC	Defense Technical Information Center
GPS	global positioning system
IEEE	Institute of Electrical and Electronics Engineers
SE	standard error
T	tactile
UAV	unmanned aerial vehicle
V	visual
VR	virtual reality
VT	visual-tactile
VvT	visual versus tactile
VvVT	visual versus visual-tactile comparison

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